

Age determination of the HR 8799 planetary system using asteroseismology

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ABSTRACT

Discovery of the first planetary system by direct imaging around HR 8799 has made the age determination of the host star a very important task. This determination is the key to derive accurate masses of the planets and to study the dynamical stability of the system. The age of this star has been estimated using different procedures. In this work we show that some of these procedures have problems and large uncertainties, and the real age of this star is still unknown, needing more observational constraints. Therefore, we have developed a comprehensive modeling of HR 8799, and taking advantage of its γ Doradus-type pulsations, we have estimated the age of the star using asteroseismology. The accuracy in the age determination depends on the rotation velocity of the star, and therefore an accurate value of the inclination angle is required to solve the problem. Nevertheless, we find that the age estimate for this star previously published in the literature ([30,160] Myr) is unlikely, and a more accurate value might be closer to the Gyr. This determination has deep implications on the value of the mass of the objects orbiting HR 8799. An age around ≈ 1 Gyr implies that these objects are brown dwarfs.

Key words: stars: fundamental parameters (mass, age) – stars: individual: HR 8799 – stars: planetary systems – stars: variables: others

1 INTRODUCTION

The discovery of the first planetary system by direct imaging around HR 8799 (Marois et al. 2008) was an important milestone in the field of exoplanet research. Up to now, eleven planets have been discovered with this procedure, and only one possible planetary system. One of the advantages of this technique is the direct measurement of the luminosity and projected orbits of the planets, making the physical characterization of the system and the individual planets possible.

Marois et al. (2008) used a procedure for estimating the mass of the objects around HR 8799 in order to discriminate whether they were real planets or brown dwarfs (BD). This procedure can be applicable to any direct imaging detection, and it is based on the comparison of theoretical evolutionary tracks of BD and giant planets with observations in an Age - Luminosity diagram. Since luminosity is a direct observable, this technique is limited by the accuracy of the age determi-

nation and the theoretical models used for this comparison (Reidemeister et al. 2009).

The A5V spectral type star HR 8799 (V342 Peg, HD 218396, HIP 114189) has been extensively studied. Schuster & Nissen (1986) firstly reported this star as a possible SX Phoenicis object (these stars are pulsating subdwarf stars with periods larger than one day). Zerbi et al. (1999) classified it as one of the 12 first γ Doradus pulsators known. This pulsating stellar type is composed of Main Sequence (MS) stars in the lower part of the classical instability strip (Dupret et al. 2005), with periods around one day. That means that their pulsating modes are asymptotic g -modes and they are suitable to study the deep interior of the star. Gray & Kaye (1999) obtained an optical spectrum of HR 8799, and assigned an spectral type of kA5 hF0 mA5 V λ Bootis (see that paper for the meaning of this specific nomenclature), reporting a metallicity of $[M/H] = -0.47$. The λ Bootis nature of the star means that it has solar surface abundances of light elements, and subsolar abundances of heavy elements, the internal metallicity of the star being unknown. They also noted that HR 8799 may be also a Vega-

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Table 1. Age of HR 8799 in the literature. The methods used are: a) Stellar kinematics groups (proper motions), b) HR diagram position compared with isochrones, c) HR diagram position compared with models, d) IR excess.

Age range in Myr	Reference	Method used
[20, 150]	Moór et al. (2006)	a
[30, 160]	Marois et al. (2008)	a, b
[50, 1128]	Song et al. (2001)	c
30	Zuckerman & Song (2004)	a, b
30	Rhee et al. (2007)	a, b
[30, 730]	Chen et al. (2006)	a, b, d

type star, characterized by a far IR excess due to a debris disk. Up to now, only three λ Bootis stars have been reported to be γ Doradus pulsators: HD 218427 (Rodríguez et al. 2006a), HD 239276 (Rodríguez et al. 2006b), and HR 8799.

Marois et al. (2008) estimated the age of the star using four different methods (see Section 2 for details). The conclusion of that work was that HR 8799 is a young MS star with an age in the range [30, 160] Myr. Reidemeister et al. (2009) added another element for estimating the age of this star: the infrared excess ratio, studied by Su et al. (2006) and also used by Chen et al. (2006). None of these determinations are conclusive, as we explain in Section 2.

In this work, a comprehensive modelling of HR 8799 has been done in order to estimate its age and mass. The λ Bootis nature of this star, and its γ Doradus pulsations are the bases of the determinations presented here. All the technical details are presented in an accompanying paper (Moya et al. 2010, Paper I), where, a complementary study on the λ Bootis nature of this star is developed.

2 PREVIOUS AGE DETERMINATIONS OF HR 8799

Most of the procedures to determine the age of isolated stars in the literature, such as activity, surface lithium abundance, or the position in the HR diagram, are useful for young and for low-mass stars, however these procedures cannot be accurately applied to an A5 MS star.

Kaye and Strassmeier (1998) studied the chromospheric activity of some γ Doradus stars, in particular HR 8799, using the Ca II H&K lines, and found that all the stars studied have very low activity, HR 8799 being the least active of all. This conclusion has an impact in its age determination since activity decreases with age in the early evolutionary stages of the star (Soderblom, Duncan, & Johnson 1991). The very low activity of HR 8799 suggests that it is a Main Sequence star.

HR 8799 has a debris disk that has been used for an estimation of its age. Zuckerman & Song (2004); Moór et al. (2006) studied the age of a number of stars with debris disks, searching for a relationship between the fractional IR luminosity $L_{\text{IR}}/L_{\text{bol}}$ and the age. HR 8799 was present in the samples covered in these works; they estimated an age of 30 Myr (Zuckerman & Song 2004; Rhee et al. 2007) or in the range [20, 150] Myr (Moór et al. 2006). Note that this age estimation was purely statistical, and has to be taken it with

caution. In addition, the debris disks have cataclismic origins (i.e. highly chaotic and unpredictable), and hardly can be related with the age of the star.

Marois et al. (2008) used four methods for estimating the age of HR 8799. The first one was the measurement of its radial velocity and proper motion (UVW). Comparing with other stars and associations with similar values of these quantities, they found an age range similar to that reported in previous works using also proper motions ([30, 160] Myr). They warned that this method is not always reliable.

The second method was the position of the star in the HR diagram (for instance, see Pont & Eyer 2004). Comparing this position with isochrones of known stellar clusters one can infer upper limits to the age of the star. This argument was used to confirm the age obtained with the statistical UVW method. Nevertheless, the λ Bootis nature of this star, and its unknown internal metallicity, makes the HR diagram position of the star an inaccurate method for the estimation of the star. Song et al. (2001) studied the age of a set of A-type stars (in particular HR 8799) using Strömgren photometry and isochrones, taking into account the stellar rotation. They concluded that, regarding the position in the HR diagram, the age estimated for this star is in the range [50, 1128] Myr.

The third method was based on the fact that λ Bootis stars are generally young. This argument is not correct. Paunzen et al. (2002) found that most of the known λ Bootis stars are stars between the ZAMS (zero-age main sequence) and the TAMS (terminal-age main sequence), with a mean age of 1 Gyr.

The fourth method was based on the assumption that γ Doradus pulsators are probably young stars. There is no evidence for this assertion. γ Doradus pulsations are originated from the blocking of the radiative flux at the base of the outer convective zone (Guzik et al. 2000). Therefore, it is mainly a thermodynamic effect, dominated by the temperature of the star and the efficiency of the convective transport. The existence, or not, of γ Doradus pulsations does not provide information about the age of the star, at least for a range in ages within the main sequence.

Table 1 shows a summary of the different age determinations of this star found in the literature.

3 ASTEROSEISMOLOGICAL ESTIMATION OF THE AGE OF HR 8799

In the previous section we indicated that there is no method that can clearly provide the age of the HR 8799 planetary system. Of all the methods mentioned in the previous section, three seems to support a young age for our star. Of those, we will only consider those based on proper motions and on the position in the HR diagram, the third being an statistical method (viz., the luminosity of debris disks) with little accuracy in age determination. Our first step is to revise the physical parameters of the star and its position in the HR diagram with the aim of checking whether the overlap in ages provided by this method and the proper motions is supported

Gray & Kaye (1999) obtained spectroscopic observations of this star, providing accurate values for the stellar luminosity, T_{eff} , and $\log g$ (see Table 2). The use of different

Table 2. Physical characteristics of HR 8799

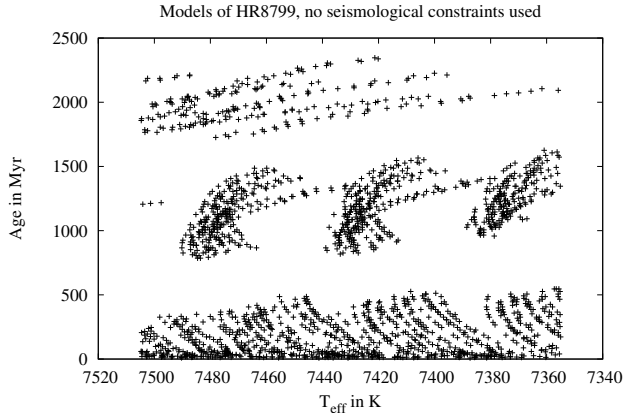
T_{eff} (K)	7430 ± 75	Gray & Kaye (1999)
$\log g$ (cm s^{-2})	4.35 ± 0.05	
$L(L_{\odot})$	4.92 ± 0.41	
$v \sin i$ (km s^{-1})	37.5 ± 2	Kaye and Strassmeier (1998)
π (mas)	25.38 ± 0.85	van Leeuwen (2007)

bolometric corrections changes significantly the value of the luminosity of the star. We have used the Virtual observatory tool VOSA (Bayo et al. 2008) to avoid the necessity for estimating the stellar luminosity using bolometric corrections. Models with realistic metallicities best fitting the observations provide a luminosity only $0.1 L/L_{\odot}$ larger than that given in Gray & Kaye (1999) and, therefore, within the errors. On the other hand, the use of different parallaxes in the literature changes the value of the absolute magnitude of this star by less than $0.1 L/L_{\odot}$ (see Paper I for details).

We have developed a grid of equilibrium models obtained with the CESAM code (Morel & Lebreton 2008), with physics appropriate for main sequence A type stars (see Paper I). In particular, the abundance mixture used is that given in Grevesse & Noels (1993). To obtain the initial hydrogen and helium abundances we have used a primordial helium content $Y_P = 0.235$ and a mean enrichment law $\Delta Y/\Delta Z = 2.2$. The use of other determinations of these parameter in the literature (Claret & Willems 2002, for example) does not change significantly the initial abundances used. The main approximation taken in the models with a possible influence in this study is the absence of updated internal chemical transport mechanisms in the equilibrium models. We vary the mass (in the range $[1.25, 2.10] M_{\odot}$ with steps of $0.01 M_{\odot}$), the metallicity (with values $[M/H] = 0.08, -0.12, -0.32, \text{ and } -0.52$), the Mixing-Length parameter MLT (values 0.5, 1, and 1.5), and the overshooting (values 0.1, 0.2, and 0.3). The internal metallicity has been regarded as a free parameter due to the λ Bootis nature of the star, which does not represent its internal abundances. The mass, estimated to be $1.47 \pm 0.3 M_{\odot}$ by Gray & Kaye (1999), has been also regarded as a free parameter since it has not been directly determined.

If we search for models fulfilling the temperature, $\log g$, luminosity and radius observed for the star, only a small amount of them remain, all in an age range $[10, 2337]$ Myr (Fig. 1). A 18.1% of the models has the age estimated in the literature for this star ($[30, 160]$ Myr). The gaps in the figure are due to the mesh of our grid of models. This result shows that the HR diagram position alone is not an accurate method to estimate the age of HR 8799. The reason is the unknown internal metallicity of the star due to its λ Bootis nature. Therefore, we need additional information to estimate the age of this planetary system.

A comprehensive asteroseismic modelling of HR 8799 have been also developed. We use the presence of γ Doradus pulsations found in this star. As γ Doradus stars are asymptotic g-mode pulsators, they are very good candidates for testing the internal structure of the star, in particular its internal metallicity and age, both having a large influence in the buoyancy restoring force, measured through the Brunt-Väisälä frequency (Moya et al. 2005; Smeyers & Moya 2007;


Figure 1. T_{eff} - Age diagram for the models of our grid fulfilling the spectroscopic observations, i.e., T_{eff} , $\log g$ and luminosity (see Table 2). The age range obtained is $[10, 2337]$ Myr.

Miglio et al. 2008). To do so, some of the most updated tools adapted for this purpose are used: 1) the evolutionary code CESAM (Morel & Lebreton 2008), and 2) the pulsation code GraCo (Moya et al. 2004; Moya and Garrido 2008). The latter has been tested in the work of the ESTA activity (Moya et al. 2008; Lebreton et al. 2008, Evolution and Asteroseismic Tools Activities). Using these tools, we performed a theoretical study of HR 8799 in an attempt at constraining physical and theoretical parameters. In this work we will follow the same scheme used for the study of the δ Scuti pulsators RV Arietis, 29 Cygnis and 9 Aurigae (Casas et al. 2006, 2009; Moya et al. 2006).

A description of the tools and procedures used can be found in Paper I. In this work we focus only on the determination of the mass and age of the star. These two quantities are the physical properties of the star with a larger impact in the understanding of the nature of the planetary system.

An important unknown for the present study is the rotation velocity. Kaye and Strassmeier (1998) gave a projected rotation velocity for this star of $v \sin i = 37.5 \pm 2.0 \text{ km s}^{-1}$. Therefore, an accurate determination of v moves to an accurate determination of the visual angle i . Several works in the literature tried to provide estimations for i with no conclusive results. This is an important condition for the modelling.

In the present study, we use the Frequency Ratio Method (FRM) developed in Moya et al. (2005) (see Section 3.3 of Paper I) for the asteroseismological modelling of this star. The FRM is based on the analytical description of the frequencies in the asymptotic regime. This procedure has a limited range of validity in stellar rotation velocities, as demonstrated in Suárez et al. (2005). In that paper, the authors found a maximum rotation velocity for the correct application of the FRM, for a standard γ Doradus star, of around 60 km s^{-1} . On the other hand, Turcotte & Charbonneau (1993) found that meridional circulation cannot destroy the accretion pattern (in the accretion/diffusion scenario, based on the accretion of interstellar medium by the star, and the mixing of these elements in the stellar surface due to diffusion and rotationally mixing processes) for a rotation velocity below 125 km s^{-1} . For

Table 3. Acceptable models depending on the physical constraints. In the less favorable case, the first (second) mass range is linked with the first (second) age range shown.

Constraint	Mass in M_{\odot}	Age in Myr	% of models with [30, 160] in Myr
HR position	[1.25, 1.27], [1.32, 1.35], [1.40, 1.48]	[10, 2337]	18.1
Complete procedure	1.32	[1126, 1486]	0.0
Comp. proc. (less favorable case)	[1.32, 1.33], [1.44, 1.45]	[1123, 1625], [26, 430]	16.7

a larger rotation velocity, theory cannot ensure that the accreted abundances can remain in the stellar surface enough time to be observed. These values provide two lower limits for the inclination angle.

Obtaining the rotation velocity as a function of i for any stellar radius in the observed range we found that $i > 18^{\circ}$ would be the requirement imposed by the λ Bootis nature of HR 8799, and $i > 36^{\circ}$ would be the requirement for the FRM to be applicable. We want to point out that if the inclination angle is between both values, our analysis would be possible but inaccurate, since we cannot ensure that the real solution is part of that provided by the FRM (Suárez et al. 2005).

Our first study was done for a moderate rotation case in the Frequency Ratio Method. This means an inclination angle $i \approx 50^{\circ}$ and a rotation velocity $V_{\text{rot}} \approx 45 \text{ km s}^{-1}$. In this case, the complete procedure is very discriminant and only models with $M = 1.32 M_{\odot}$ fulfill all the observational constraints. The acceptable age range is [1126, 1486] Myr, far from the value estimated for this star by Marois et al. (2008) ([30, 160] Myr). In Fig. 2 (left panel), the acceptable set of models for this rotation velocity is shown in a T_{eff} -Age diagram. The T_{eff} axis limits are provided by the spectroscopic observations.

We have also studied the less favourable case in the FRM, i.e. an inclination angle $i \approx 36^{\circ}$, that is, $V_{\text{rot}} \approx 60 \text{ km s}^{-1}$. In this case, the complete procedure is not completely discriminant and new models fulfill all the observational constraints. Two mass ranges are now acceptable ($M = [1.32, 1.33]$ and $[1.44, 1.45] M_{\odot}$), and the compatible age range is divided into two blocks: [1123, 1625] Myr and [26, 430] Myr respectively (Fig. 2, right panel). The two models with ages around 800 Myr have been accepted due to the conservative application of the instability analysis (see Paper I), but it their belonging to the set of acceptable models is unlikely. In this less favourable case, the percentage of accepted models with ages in the range commonly used for this star is 16.7%. A summary of the results presented here is found in Table 3.

4 CONCLUSIONS AND FUTURE PERSPECTIVES

In the present work, an analysis of the age determination of the planetary system HR 8799 has been done. The results found in the literature are not conclusive, and the only valid argument to estimate the age of the star is that using its radial velocity and proper motion, but it is an estatistical argument needed of additional estimations.

The only valid argument used to estimate the age of the star is its radial velocity and proper motion, but it is a statistical argument needed of additional estimations. The

main complementary argument is the position of the star in the HR diagram. In this work we have demonstrated that this procedure does not provide accurate age estimations due to the λ Bootis nature of HR 8799. This nature hides the real internal metallicity of the star. The main consequence of this result is that the models fulfilling observations are in a range of ages [10, 2337] Myr, a much broader range that one estimated by other authors of [30, 160] Myr (Marois et al. 2008). Only a small amount (18.1%) of models in our representative grid have ages in the range claimed in the literature.

Therefore we need additional constraints for an accurate estimation of the age and mass of the star (these two quantities are the physical characteristics of the star with larger impact in the understanding of the planetary system). We have taken advantage of the γ Doradus pulsations of the star to better estimate these values with the help of asteroseismology.

A comprehensive asteroseismological study of this star has been developed. This study is described in detail in (Moya et al. 2010, Paper I). The main source of uncertainty of the procedure is the unknown rotation velocity of the star. We have analysed the possible results depending on the inclination angle i . There is a range of angles where this study is not accurate ($i = [18^{\circ}, 36^{\circ}]$).

For angles around $i = 36^{\circ}$, the models fulfilling all the observational constraints have masses in two separate ranges of $M = [1.32, 1.33]$, [1.44, 1.45] M_{\odot} . The age of the system is constrained in two separate ranges: [1123, 1625] Myr and [26, 430] Myr respectively. A percentage of 16.7% of the models are in the range given in the literature, i.e., young ages. A consequence of this result is that, in the case of the youngest age range, the predicted masses of the observed planets are [5, 14] M_{Jup} for the most luminous planets, and [3, 13] M_{Jup} for the less luminous one. The oldest age range predicts masses for the three objects in the brown dwarfs domain (see Fig. 4 of Marois et al. 2008).

In the most favourable case for the procedure used in this work, i.e. inclination angles of around $i \approx 50^{\circ}$, asteroseismology is very accurate, and the star would have an age in the range [1126, 1486] Myr, and a mass $M = 1.32 M_{\odot}$. This age range implies that the observed objects orbiting HR 8799 would be brown dwarfs (following Fig. 4 in Marois et al. 2008).

The lack of an accurate determination of the inclination angle is the main source of uncertainty of the present study. This angle has not been unambiguously obtained up to now, and its value would say whether the results of this study are actually applicable, and then, it can provide a very accurate determination of the age and mass of the star. In any case, one of the main conclusions of our study is that the range of ages assigned to this star in the literature is unlikely to be

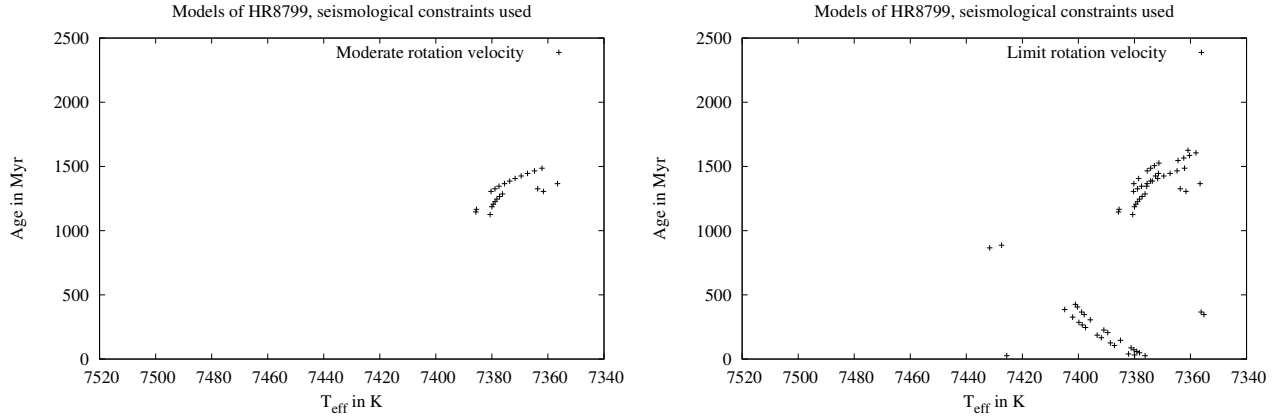


Figure 2. T_{eff} - Age diagram for the models of our grid fulfilling the spectroscopic observations plus all the asteroseismological constraints (FRM + multicolour photometry + instability analysis, see Paper I) for a rotation velocity $V_{\text{rot}} \approx 45 \text{ km s}^{-1}$ (left panel) and $V_{\text{rot}} \approx 60 \text{ km s}^{-1}$ (right panel). The age ranges obtained are [1123, 1625] Myr and [1123, 1625], [26, 430] Myr, respectively

the correct one. Only a stellar luminosity larger than that reported would allow young models with solar metallicity to fulfill all the observational constraints.

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